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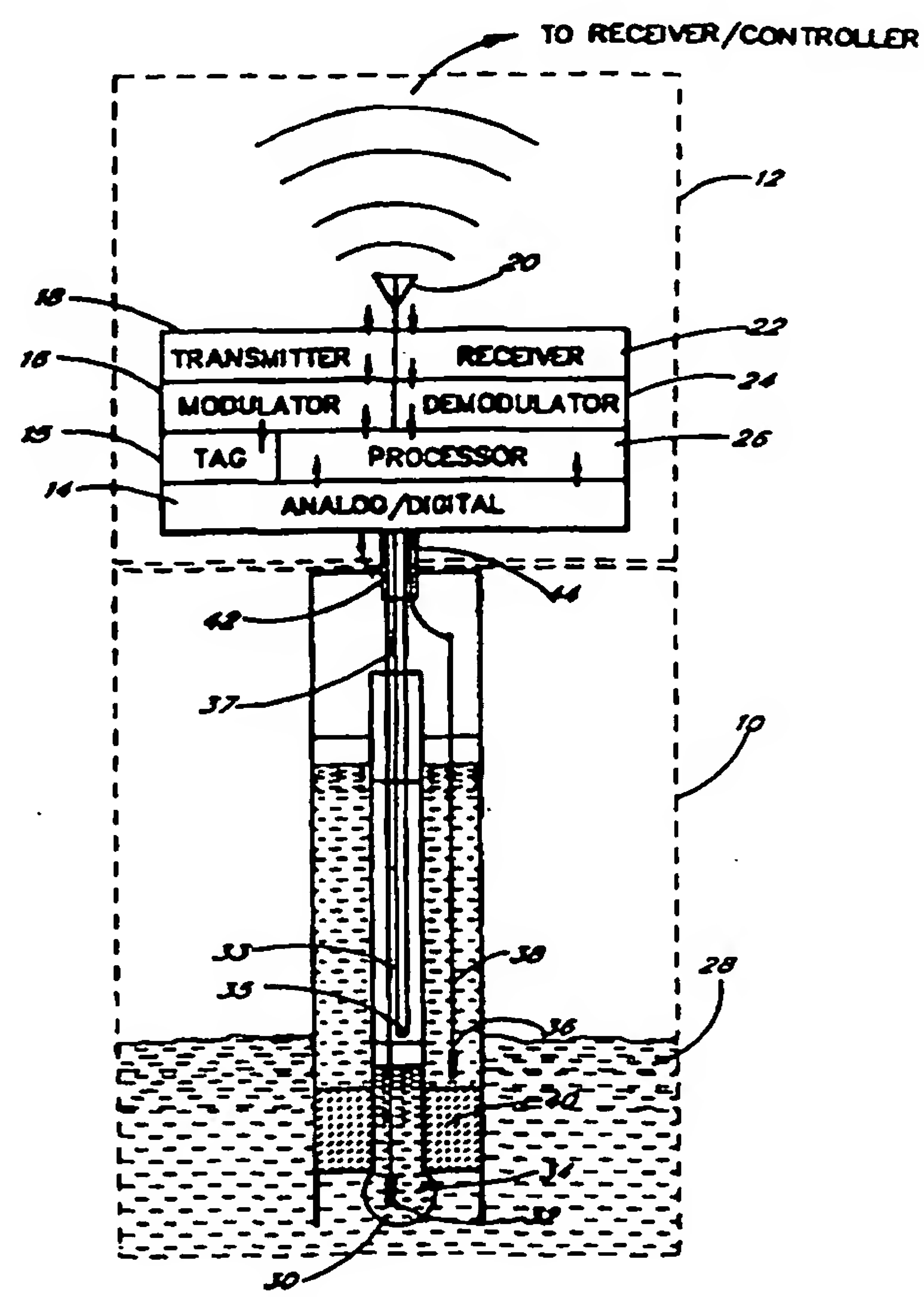
(54) Title: WIRELESS TELEMETRY FOR ION SENSING

(57) Abstract

An ion concentration sensing transducer is utilized as the source of encoded information on a wireless carrier signal to form a telemetric ion sensor. The apparatus comprises principally an ion sensing transducer, whose ouptut is coupled directly into a subcarrier modulator. The subcarrier modulation is preferably an analog to digital conversion, thereby providing for compatibility with a variety of other digital apparatus and operations. The subcarrier is encoded on a carrier signal for wireless transmission therefrom. The telemetric ion sensor is advantageously incorporated into a distributed telemetric process control system, whereby the telemetric sensor provides remote process output information to a process controller. Based on this information, the process controller generates process control information which is in turn telemetered to a process control apparatus which executes the process input instructions.



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WIRELESS TELEMETRY FOR ION SENSING

Field of the Invention

The present invention relates generally to telemetric ion concentration sensing, and in particular to wireless remote communication and control of ion sensors.

Background of the Invention

The concentration of an ionic chemical species in solution may be determined by measuring the chemical potential or activity manifest as a potentiostatic variation between an indicator and reference electrode. In general, for such purposes as ion sensing, the practice is to immerse an indicator and reference electrode in the solution containing the unknown ion concentration. While the potential of a reference electrode may be considered substantially constant and independent of ion concentration, the potential of the indicator or sensor electrode, preferably ion-specific, is sensitive to and changes with the specific ion concentration. The potential difference V_m between these two electrodes changes in a well-defined, predetermined manner with respect to the ion concentration a_i, often accurately described by the Nernst equation:

$$V_m = V_0 + \frac{RT}{z_i F}\ln(a_i) \qquad (1)$$

where V_0 is a reference potential, R is the gas constant, T is the absolute temperature and F is the Faraday constant. Here, z_i is the ionization state of ion-i. Ion sensing electrodes come in a variety of forms ranging from the well-known glass membrane electrodes to integrated ion-selective field-effect devices. An important practical example is the glass bulb hydrogen ion (H^+) electrode having a potentiometric output proportional to the logarithm of the H^+ activity or pH. Hydrogen ion electrodes measure the effective acidity or alkalinity of aqueous solutions.

The electrochemical potentials generated by an ion-sensing electrode originate across the surface boundary layer of a permselective membrane, such as an alkali ion-doped silicate glass. The membrane, as such, should be permeable enough to establish an electrochemical potential within a desirably short measuring time, and yet not too permeable so as to perturb the chemical equilibrium. Hence, such electrodes are typically high impedance devices, with output impedance commonly in the megaohm regime. The output signals generated by such high impedance sources as ion specific electrodes are susceptible to noise and drift, and therefore are preferably transmitted via shielded electrical conduit to a suitable transimpedance or buffer amplifier. Once amplified, the signal may be transmitted accurately over longer distances via coaxial cable to a remote location for measurement and analysis. The electrode signals, often in the millivolt range, are monitored by a sufficiently high-impedance electrometer or potentiostatic bridge so as not to perturb either the membrane potential or amplified signal.

The technology of pH sensors and ion sensing in general has received considerably attention over

the years, with attendant advances in measurement accuracy, long term stability and associated electronics. A more detailed description of ion sensing and electrode structure are provided in U.S. Patent No. 4,128,468 by G.L. Bukamier. In spite of these improvements in the ion-selective electrode art, in general most electrode signals are transmitted via coaxial cable from the signal source to the signal monitor. For applications such as intelligent chemical process control, hazardous waste treatment monitoring and physiological diagnostics among others, the ion sensing is often performed remotely and the measurements telemetered to a monitor and control location. While cable transmission of measured signals is frequently performed, it often presents serious limitations in terms of cost, bulk, versatility and efficiency. It is, therefore, highly desirable to perform telemetric ion sensing where such signals are transmitted via wireless means to a remote location for such purposes as process measurement and control.

For decades telemetry has been a topic of considerable interest and development, particularly in aerospace, industrial process control and physiological diagnostics. Given the myriad of telemetric applications it is not too surprising that telemetry systems come in a variety of forms depending intimately upon the intended environment as well as the physical quantity being measured. Broadly stated, wireless radio telemetry systems comprise (1) transducers to convert the physical measurement into electrical signals, (2) a radio transmitter, modulated by the transducer signal, (3) a receiver/demodulator to extract the measured signal after transmission. While transmitters and receivers can take full advantage of a highly developed radio technology, transducers themselves often require considerable care in design, fabrication, calibration and maintenance to obtain the desired accuracy and reliability.

pH sensing and ion sensing in general represents a particularly challenging class of telemetry because of the wide range of often harsh environmental conditions associated with remote process control. Even for routine applications, the generally small sensor output signals originate from a high impedance source, which, as previously mentioned, is often subject to noise and drift. In such circumstances, the sensor signal can be buffered before radio modulation and transmission, which adds bulk and expense to a potentially compact system. For example, U.S. Patent No. 5,199,428, granted to I.W.P. Obel and I. Bourgeois, disclose an implantable electrical nerve stimulator/pacemaker in which a subcutaneous pH sensor utilizes a signal conditioning interface and additional process control prior to a two-way telemetric communications link. Orion Research has also disclosed a benchtop, research grade pH meter/controller having remote radio frequency communication with up to four pH electrodes.

Summary of the Invention

The present invention provides an effective, cost beneficial, accurate and reliable telemetric ion sensor. In accordance with one aspect of the present invention, a telemetric ion sensor begins with an ion sensing signal transducer that converts the influence of an ionic chemical species to an electrical signal indicative of the ion concentration. The signal is supplied to a generator of subcarrier signals whereupon the electrical signal is encoded in a subcarrier signal. The encoded subcarrier signal is then supplied to a

modulator which modulates a carrier signal with the subcarrier signal. The modulated carrier signal is subsequently transmitted as a wireless electromagnetic signal for reception at a remote location. While the transducer signal may be encoded as an analog signal, it is preferable to telemeter digitally encoded information, consequently, a preferred embodiment of a telemetric ion sensor incorporates an analog to digital conversion before the carrier modulation. Furthermore, the sensor is preferably supplied with a temperature sensing transducer which supplies information for use in temperature compensation and other process control functions. The temperature information is preferably telemetered with the ion concentration information. Still further, a sensor signature tag is preferably encoded on the carrier to associate the sensor of origin with the transmitted information.

In accordance with another aspect of the present invention, a method of remote ion sensing comprises first generating an information signal indicative of the remote ion concentration. The information signal is then encoded on a subcarrier signal, which is in turn used to modulate a carrier signal. The modulated carrier signal is then transmitted as a wireless electromagnetic signal. The steps comprising the information encoding preferably also include information relating to the ambient temperature and sensor signature information.

In accordance with yet another aspect of the present invention, a telemetric process control system is comprised of a telemetric ion sensor, a process controller and a telemetric process control apparatus. In a preferred embodiment of the telemetric process control system, the telemetric ion sensor transmits process information to the process controller. The process controller generates process control information, preferably on the basis of the received process information. The process control information is then telemetered to the process control apparatus whereupon process input instructions are carried out. In another preferred embodiment, the process controller may reside in either of the telemetric sensor or telemetric control apparatus, to comprise a remote, intelligent process control system.

A significant feature of the present invention is that it provides for an effective solution for those applications in which ion sensing and process control must be performed in harsh, hazardous or otherwise remote environments.

Brief Description of the Drawings

Figure 1 is a schematic x-section of an ion sensor configured as a signal transducer in a telemetric ion sensing apparatus.

Figure 2 is a functional block diagram of a telemetric process control system utilizing a telemetric ion sensor.

Detailed Description of the Preferred Embodiments

It is illustrative to consider the presently contemplated preferred embodiments within the context of a commonly used glass-membrane ion sensor, which itself makes advantageous use of the present preferred method and apparatus for telemetric ion sensing and process control. Accordingly, as an aid to

fully appreciating the present invention, a brief description of an exemplary ion sensor initially follows.

As shown in Figure 1, an ion sensor functioning as a signal transducer in a telemetric arrangement may comprise a conventional ion sensitive electrode subassembly 10. The ion specific electrode 10, generally comprises an ion-specific bulbous membrane 30, comprised of a variety of ion-specific permeable glasses well-known in the art, shaped to form an enclosure separating a test solution 28 from an internal electrolyte 34. The internal sensing electrode 32 is disposed within the enclosure defined by the membrane 30 and is submerged in the internal electrolyte 34. Such electrodes are for example comprised of a composite Ag/AgCl material well-known in the art. The internal electrolyte is commonly a buffered KCl solution, maintained at known pH values (e.g. pH 7.0). The sensing electrode 32 is connected to an electrical conductor 33 leading out of the cell to form the half-cell output signal connection.

When placed in a test solution, the aforementioned ion-sensing half-cell generates an electrochemical potential that must be measured with respect to a reference potential. In the exemplary embodiment shown in Figure 1, the reference half-cell is comprised of a liquid junction 40 providing a low-impedance interface between test solution 28 and reference electrolyte 38. The reference electrode 36 is also comprised of a Ag/AgCl composite material, and is immersed in a reference electrolyte 38. As before, the reference electrolyte may be a buffered KCl solution. The reference electrode 36 is connected to an electrical conductor 37 leading out of the cell as the reference potential output connection. A more detailed description of an exemplary ion sensing probe is provided in U.S. Patent No. 4,128,468 by G.L. Bukamier, incorporated herein by reference. In operation, the reference potential remains substantially constant, independent of the ion concentration in test solution 28. Together, the potential difference between the signal potential and reference potential comprises a signal S which is a measure of the ion concentration a_i of the test solution 28.

As is apparent in the Nernst equation (1), the sensitivity of an ion sensor is dependent upon the ambient temperature. Hence, a temperature sensor is commonly disposed in a region near the ion sensing junction 30 in a manner allowing accurate temperature measurement of the junction. The type and configuration of the temperature sensor may take a variety of forms depending upon the specific application. As shown in Figure 1, for example, a temperature sensor may comprise a Pt-100 or Pt-1000 thermo-resistive element whose resistance is calibrated with respect to the ambient temperature. The temperature of the thermo-resistive element 35 is sensed via a resistance measurement applied across the conducting leads 37. The resulting precalibrated signal is used to compensate the ion sensor reading in accordance with a predetermined temperature dependent behavior.

For applications where it is desirable to remotely perform ion sensing and process control, the above described exemplary ion sensor may be configured to telemeter the measured ion concentration signal by wireless means. As shown in Figure 1, the ion sensor 10 is configured to be a signal transducer for an electro-magnetic (EM) transmission subassembly 12. The EM subassembly 12 may take a variety of forms

well-known in the telemetry art, generally comprising (1) a generator of subcarrier signals which is modulated by the transducer signal S, (2) a generator of EM carrier signals which the subcarrier modulates, hereinafter referred to as the modulator (3) a transmitter and (4) an antenna. As further shown in Figure 1, the subcarrier generator preferably comprises a means for pulse code modulation or analog-to-digital (A/D) conversion 14. The A/D conversion is followed by the EM modulator 16, the EM transmitter 18 and antenna 20.

In operation, the A/D converter 14 samples the analog signal representative of the measured electrochemical potential S for a predetermined time at predetermined sampling intervals. The sampled signal is quantized in accordance with a predetermined discrete scale and converted to a digital signal D, comprising a binary data stream indicative of the sign and magnitude of the potential. The A/D converter may also include a transimpedance or buffer amplifier to provide a downstream signal impedance more suitable for processing and transmission. The digitized signal D is supplied to the modulator 16 at which stage the digitized sensor signal D is encoded on the EM carrier. The technique used for encoding or modulating the EM carrier by the subcarrier signal D may involve any of a variety of methods well-known in the art and generally characterized by digital versions of amplitude modulation, frequency modulation or phase modulation techniques (including combinations thereof). Additionally, depending upon the desired transmission range, the EM signal R may be amplified before it is supplied to antenna 20, for transmission therefrom. Alternatively, the EM signal R may be transmitted to, and received by, any number of signal repeaters for increased range and power boost.

The foregoing description of a preferred telemetric ion sensor is advantageously extended to incorporate temperature compensation in a variety of ways. A preferred method and apparatus for temperature compensation employs a resident temperature sensor 35 and signal processor 26. The temperature sensor 35, as described earlier, generates an electrical signal indicative of the ambient temperature. The ion sensor output and temperature sensor output are supplied to the resident signal processor 26, preferably in a digital format (after A/D conversion), which generates a temperature compensated ion concentration signal in accordance with a predetermined temperature dependent behavior. Furthermore, the temperature signal as well as the ion concentration signal is preferably encoded for telemetry in accordance with the foregoing description. Hence, a preferred telemetric ion concentration sensor will transmit information pertaining to the process temperature as well as the measured ion concentration.

In a complex chemical process, it is common to employ multiple ion sensors which sense different stages of the process or different chemical species present in the process. In such circumstances, it is highly desirable to clearly associate the sensed information with it's source. In a another preferred embodiment of a telemetric ion sensor, provision is made in the telemetry apparatus for an electronic identification or tag, which will identify the sensor of origin in the transmitted signal. In the embodiment depicted in Figure 1,

the electronic tag unit 15 supplies the modulator 16 with an additional signal distinct from other telemetric sensor units. The transmitted signal carries this signature along with the sensor information. The presently disclosed preferred embodiment is also advantageous because a plurality of tagged sensor signals may be readily multiplexed for transmission and demultiplexed at a remote receiver.

In yet another preferred embodiment, the telemetry apparatus is additionally provided with an EM receiver 22 and demodulator 24, enabling the resident processor 26 to receive and process information. In a presently contemplated preferred embodiment, the resident processor is desired to perform such functions as temperature compensation, sensor calibration or distributed process controlling functions.

The above described preferred embodiment of a telemetric ion sensor is advantageously incorporated as a key feature in an intelligent, remote process control apparatus as depicted in Figure 2. The distributed process control system 50 utilizes a central process monitor and control station 60 comprising a local process controller 62 which is connected to a EM encoder/decoder 64 and wireless EM transmitter/receiver 66. The remote process 68 to be monitored and controlled is connected to the telemetric process sensor apparatus 70, in this case comprising an ion sensor 72, A/D converter 74, processor 76, EM encoder/decoder 78 and EM transmitter/receiver 79. As previously described in connection with Figure 1 and shown schematically in Figure 2, the output of the process ion sensor 72 is preferably connected to the A/D converter 74. The output of the A/D converter 74 is connected to the digital signal processor 76, which is connected to the EM encoder/decoder device 78 and the EM transmitter/receiver 79. The process 68 is also connected to the telemetric process control apparatus 80, comprising the control apparatus 82, a digital-to-analog (D/A) converter 84, digital signal processor 86, EM encoder/decoder 88 and wireless EM transmitter/receiver 89.

The remote process 68 is generally controlled by a set of process control instructions, such as for example a process control algorithm, which specifies process input variables $u(t)$ 81, on the basis of measured process output variables $y(t)$ 71. Examples of such process input variables may be pressure, temperature or concentration of one or more chemical species. In accordance with the present preferred embodiments, the process output variables $y(t)$ 71 include the ion concentration sensor output $S(t)$. In operation, the process control generator comprises principally a software/hardware implementation in process controller 62 of the central process monitor and control apparatus 60. Instructions for process input $u(t)$, provided by the process controller 62 are encoded on an EM carrier by the encoder 64 and transmitted 77 by transmitter 66 to the telemetric process control apparatus 80. Process control instructions are received by receiver 89 of the telemetric process control apparatus 80. They are subsequently decoded by the decoder 88 to supply processor 86 with a digital data stream of process control instructions. The processor 86 supplies digital control input instructions to the D/A converter 84 to produce analog control input instructions $u(t)$. The control input $u(t)$ 81 is applied to the control apparatus 82 which influences the process 68 in accordance with the control algorithm. In other embodiments, the control apparatus 82 may operate directly on the digital control input instructions, eliminating the need for the D/A converter 84. Still further, the control

instructions may comprise analog signals

The process input u(t) is generated by the control algorithm residing in the process controller 62, on the basis of process output information y(t) 71 generated by the telemetric ion sensor apparatus 70. The specific process ion concentration 71 is sensed by sensor 72 and converted to a digital representation by the A/D converter 74. The digital process output information is supplied to the digital processor 76, which may perform a variety of operations. In the present embodiment, the processor 74 transmits the digital process output data to the EM encoder 78 for encoding the digital information on an EM carrier signal. The processor 76 may, for example, process at the temperature compensation step referred to earlier. The transmitter 79, transmits the encoded process output data 67 to the receiver 66 of the central process control apparatus 60. The process output data 67 is subsequently decoded by decoder section 64, and supplied to the process control algorithm in the process controller 62.

In another preferred embodiment of telemetric process control utilizing the telemetric ion sensor 70, the process control algorithm may in various forms, reside in either of the remote processors 76 or 86. Encoded process input/output data, such as the ambient temperature, ion concentration or process control instructions are transmitted directly between the telemetric process control apparatus 80 and telemetric process sensing apparatus 70 as indicated by the wavy transmission arrows 87 extending between the transmitter/receiver 89 and transmitter/receiver 79. Additionally, the central process controller 62 is preferably provided with the capability to override or adjust various aspects of the presently described telemetric process control loop, as would be apparent to those skilled in the art. Such adjustments may comprise, for example, sampling or control periods, response time, controller gain, or stability.

While the present invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit, scope and teaching of the invention. For example, although the present invention is described as embodied in a glass membrane ion sensor, it will be apparent that the present invention is also applicable to other types of ion sensors as well as combinations and configurations thereof. Accordingly, the embodiments herein disclosed are to be considered merely as illustrative and limited in scope only as specified in the appended claims.

CLAIMS:

1. A telemetric ion sensor comprising;

an ion sensing signal transducer for generating ion concentration information signals;

a temperature sensing signal transducer for generating temperature information signals;

an analog-to-digital converter connected to said ion sensing signal transducer and said temperature sensing signal transducer for digitally encoding the information signals on a digital signal;

a generator of signature signals;

a generator of carrier signals;

a modulator connected to said analog-to-digital converter, said generator of signature signals and said generator of carrier signals for modulating the carrier signals by the signature and digital signals; and

a transmitter connected to said modulator for transmitting the modulated carrier signals.

2. The telemetric ion sensor of Claim 1, wherein said carrier signal is an electromagnetic signal.

3. The telemetric ion sensor of Claim 2, wherein said transmitted modulated carrier signal comprises a wireless transmission.

4. The telemetric ion sensor of Claim 3, further comprising a digital signal processor connected to said analog-to-digital converter.

5. The telemetric ion sensor of Claim 4, further comprising a wireless receiver and demodulator connected to said digital signal processor for receiving transmitted signals.

6. A method of sensing an ion concentration comprising the steps of:

generating an information signal indicative of an ion concentration;

encoding the information signal on a digital signal;

modulating a carrier signal with the encoded digital signal; and

transmitting the modulated carrier signal.

7. The method of Claim 6, further comprising the step of generating an information signal indicative of a temperature.

8. The method of Claim 6, further comprising the step of generating a signature signal associated with the information signal.

9. A process control system for the remote control of process ion concentrations comprising:

at least one telemetric ion sensor in contact with said process ion concentrations, said telemetric ion sensors having ion concentration sensing signal transducers, said transducers generating process information signals, and having wireless telemeters of said process information signals;

a process controller in communication with said telemetric ion sensors, said process controller generating process control information in response to process information signals; and

a telemetric process control apparatus in communication with said process controller, said control apparatus influencing process variables in response to telemetered information.

10. The process control system of Claim 9, wherein the process controller is a telemetric process controller, said telemetric process controller having a receiver that receives telemetered process information signals and a transmitter that transmits process control information.

11. The process control system of Claim 9, wherein the process controller is connected to at least one telemetric ion sensor.

12. The process control system of Claim 9, wherein the process controller is connected to the telemetric process control apparatus.

13. A telemetric ion sensor comprising;

an ion sensing signal transducer for generating ion concentration information signals;

a temperature sensing signal transducer for generating temperature information signals; and

a telemetry apparatus connected to transmit encoded information signals in response to said ion concentration and temperature information signals.

14. The telemetric ion sensor of Claim 13, wherein the telemetry apparatus comprises:

a generator of subcarrier signals connected to the signal transducers;

a generator of a carrier signals connected to the generator of subcarrier signals;

an encoder connected to the signal transducers and the generator of subcarrier signals for encoding the information signals on the subcarrier signals;

a modulator for modulating the carrier signals by the encoded subcarrier signals; and

a transmitter that transmits the modulated carrier signals.

15. The telemetric ion sensor of Claim 14, wherein the encoder comprises a pulse code modulator.

16. The telemetric ion sensor of Claim 14, further comprising a generator of signature signals connected to the encoder, said signature signal being encoded on the subcarrier signals.

17. A telemetric ion sensor comprising;

an ion sensing signal transducer for generating ion concentration information signals;

a generator of signature signals; and

a telemetry apparatus connected to said ion sensing signal transducer and said signature generator to transmit encoded information signals in response to said ion concentration and signature signals.

18. The telemetric ion sensor of Claim 17, wherein said telemetry apparatus comprises:

a generator of subcarrier signals connected to said signal transducer and said signature generator;

an encoder connected to said generator of subcarrier signals to encode the information and signature signals on the subcarrier signals;

a generator of carrier signals connected to said encoder;

a modulator connected to said generator of carrier signals to modulate the carrier signals by the encoded subcarrier signals; and

a transmitter connected to said modulator to transmit the modulated carrier signals.

19. The telemetric ion sensor of Claim 18, wherein the encoder comprises a pulse code modulator.

20. The telemetric ion sensor of Claim 17, further comprising a temperature sensing signal transducer.

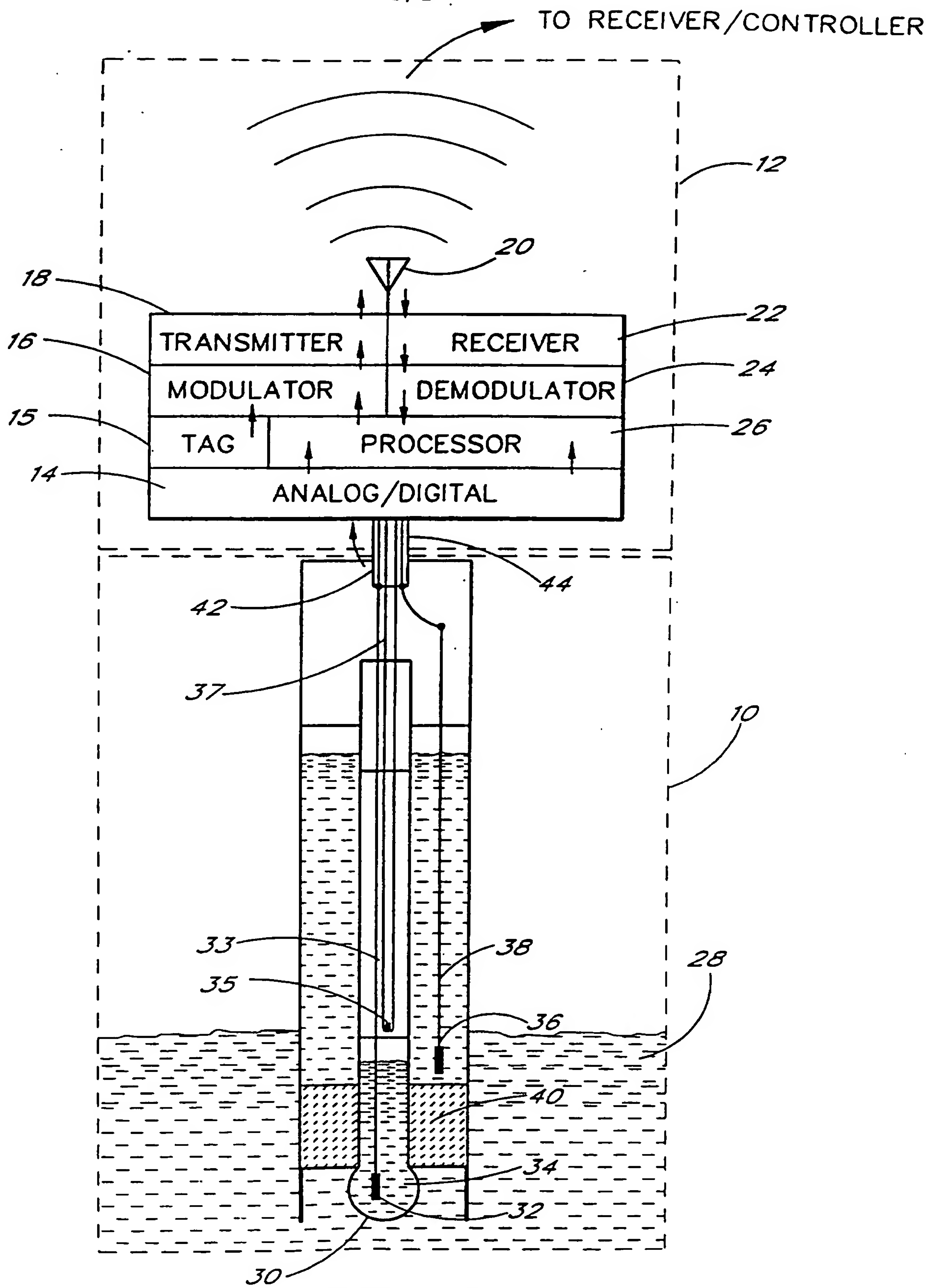
21. A telemetric ion sensor comprising:

an ion sensing signal transducer for generating an electrical signal in response to an ion concentration; and

a telemetry apparatus comprising a pulse code modulator connected to the ion sensing signal transducer for digitally encoding the ion concentration signal.

22. The telemetric ion sensor of Claim 21, further comprising a temperature sensing signal transducer connected to the pulse code modulator for digitally encoding a temperature information signal.

23. The telemetric ion sensor of Claim 22, further comprising a signature generator, said signature generator generating a signature signal associated with said ion sensing signal transducer.


TO RECEIVER/CONTROLLER
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TRANSMITTER
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FIG. 1

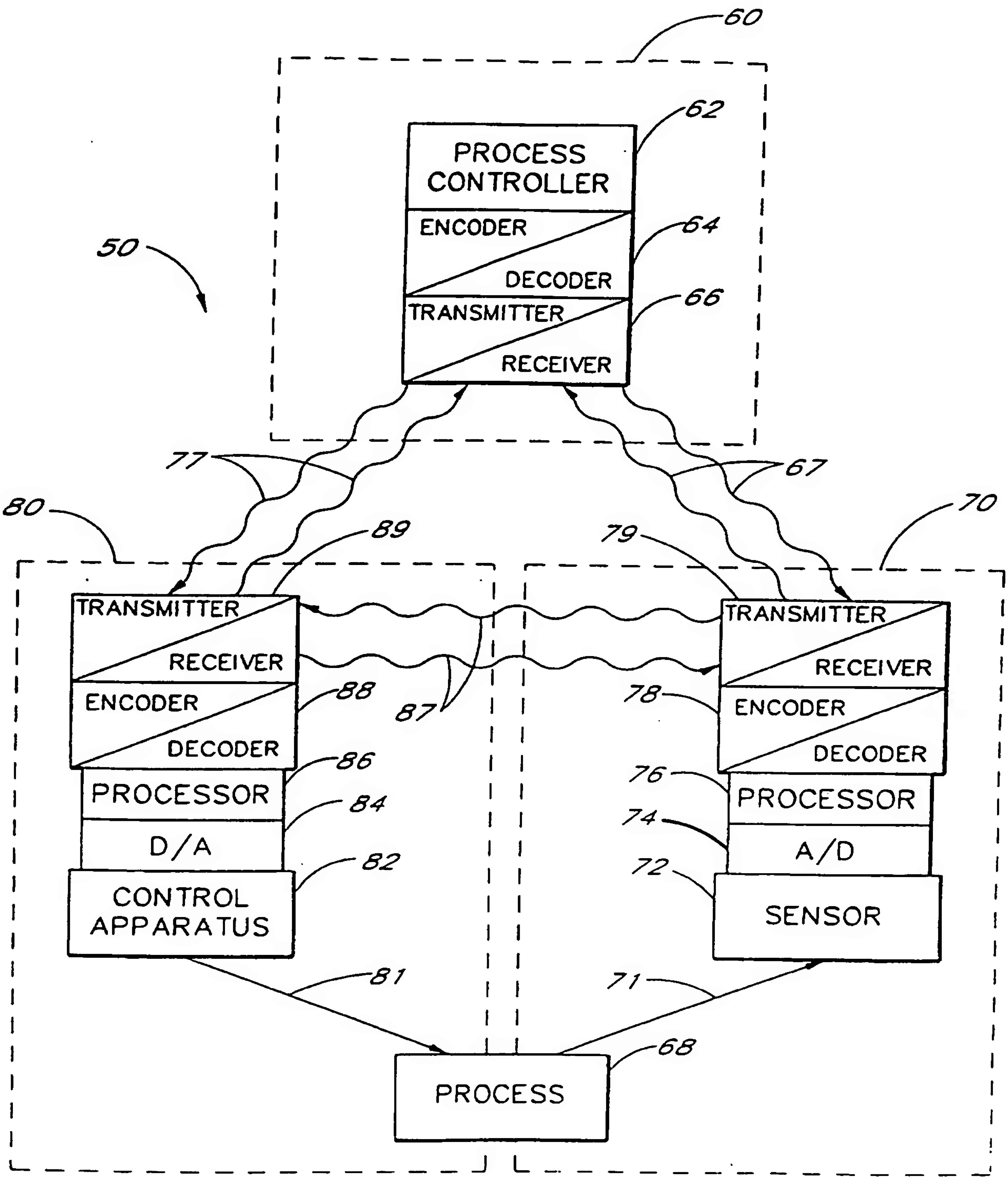

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FIG. 2

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 95/13641

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01N27/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP,A,0 138 402 (A. CUSCHIERI) 24 April 1985 see abstract; figure 1 ---	1
Y	IEEE INSTRUMENTATION AND MEASUREMENT TECHNOLOGY CONFERENCE, 25 - 27 April 1989 WASHINGTON, D.C., pages 141-145, XP 000041349 H. G. ROTITHOR 'MICROPROCESSOR BASED PH MONITORING AND TRANSMITTING SYSTEM' see the whole document ---	1
A	US,A,3 933 612 (D. J. FISCHER) 20 January 1976 see abstract --- -/--	1

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
26 February 1996	06.03.96

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

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PCT/US 95/13641

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,3 547 794 (K. NUSHIMOTO) 15 December 1970 see abstract ---	1
A	DE,A,11 54 844 (TELEFUNKEN) 16 April 1964 see claim 1 -----	1

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern al Application No
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US-A-3547794	15-12-70	DE-A-	1798192	24-02-72
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DE-A-1154844		NONE		